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Abstract

Kubernetes Operators, automated tools designed to manage application lifecycles within Kubernetes clusters, extend the functionalities of Kubernetes, and reduce the operational burden on human engineers. While Operators significantly simplify DevOps workflows, they introduce new security risks. In particular, Kubernetes enforces namespace isolation to separate workloads and limit user access, ensuring that users can only interact with resources within their authorized namespaces. However, Kubernetes Operators often demand elevated privileges and may interact with resources across multiple namespaces. This introduces a new class of vulnerabilities, the Cross-Namespace Reference Vulnerability. The root cause lies in the mismatch between the declared scope of resources and the implemented scope of the Operator's logic, resulting in Kubernetes being unable to properly isolate the namespace. Leveraging such vulnerability, an adversary with limited access to a single authorized namespace may exploit the Operator to perform operations affecting other unauthorized namespaces, causing Privilege Escalation and further impacts.

To the best of our knowledge, this paper is the first to systematically investigate the security vulnerability of Kubernetes Operators. We present Cross-Namespace Reference Vulnerability with two strategies, demonstrating how an attacker can bypass namespace isolation. Through large-scale measurements, we found that over 14% of Operators in the wild are potentially vulnerable. Our findings have been reported to the relevant developers, resulting in 7 confirmations and 6 CVEs by the time of submission, affecting vendors including the ****** and ******, highlighting the critical need for enhanced security practices in Kubernetes Operators. To mitigate it, we also open-source the static analysis suite to benefit the ecosystem.

CCS Concepts

 Security and privacy → Software and application security; Distributed systems security.

Keywords

Kubernetes, Operator, Vulnerability, Privilege Escalation, Cross-Namespace Zhaoxuan Jin Northwestern University Evanston, Illinois, USA whale3ye@gmail.com

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1 Introduction

Kubernetes has emerged as the dominant platform for container orchestration, playing a central role in the deployment, scaling, and management of containerized applications in modern cloud-native environments [5, 6, 10, 43]. As a highly extensible and open-source system, Kubernetes facilitates the automation of complex operations such as container deployment, scheduling, and management across clusters. Its flexibility and wide adoption have made it the cornerstone of many enterprise-level infrastructure solutions, offering efficient ways to handle diverse and dynamic workloads in a scalable manner.

Kubernetes organizes resources into namespaces [8], which allow users to divide a single cluster into multiple virtual clusters. Each namespace serves as a logical boundary, isolating resources like pods, services, and secrets from other namespaces within the same cluster. This isolation is essential for managing different applications or services within the same Kubernetes environment, enabling teams to work independently without interfering with each other. Namespaces also provide a way to scope access to resources, ensuring that certain actions can be confined to specific namespaces and reducing the risk of accidental or malicious interference between services.

To achieve namespace isolation, a crucial security mechanism is Role-Based Access Control (RBAC) [29]. RBAC defines roles and permissions for users, service accounts, and other entities within the cluster, helping to control which actions are allowed within the system. For example, a staff member of a team may only be allowed to manipulate resources within the namespace assigned to their team, while the cluster administrator would be assigned all permissions across namespaces. By configuring RBAC policies, administrators can limit access to resources within specific namespaces, ensuring that users or services can only interact with the resources they are authorized to access. This granularity of access control reinforces the isolation between namespaces and helps to prevent unauthorized access to sensitive resources.

While Kubernetes provides robust tools and security mechanisms to manage and secure applications, the native platform has limitations in automating the lifecycle of complex applications. Kubernetes requires significant manual intervention for tasks like scaling, upgrades, and configuration management, which can be timeconsuming and error-prone [45]. Kubernetes Operators [9] were introduced to address these limitations. Operators are programs

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that extend Kubernetes' capabilities by automating the management of applications. They encapsulate the operational knowledge required to manage complex Kubernetes applications, automating critical tasks such as deployment, scaling, and lifecycle management. Users can then easily request Operators to conduct complex operational tasks in contrast to manually manipulating raw Kubernetes resources. By automating these processes, Operators reduce the operational burden on DevOps teams and enable more consistent and reliable application management.

However, Kubernetes Operators require significant privileges to carry out their tasks. Due to the broad range of operations they need to perform, these Operators are usually granted substantial permissions across namespaces. While these permissions are necessary for the proper functioning of the Operator, they also introduce a significant security risk. Due to improper security practices in Operator implementation, adversaries may forge malicious requests toward Operators, exploit vulnerabilities to escalate their own permissions, break namespace isolation, and perform unauthorized operations within the cluster.

Although extensive research has been conducted on Kubernetes security, the issue of Operator security remains largely unexplored. Previous studies have focused on misconfiguration in Kubernetes, especially excessive RBAC permissions, highlighting the risks of overly permissive access controls [31, 47]. While these works have led to improvements in reducing permissions, they have not addressed the inherent risks that remain even when permissions are minimized. Specifically, necessary permissions may still be exploited due to improper security practices within the Operator itself. Other research has focused on bugs in Kubernetes Operators [30, 41, 46], yet these studies primarily concentrated on the functional bugs of Operators rather than their security vulnerabilities. Furthermore, existing security tools [11, 13, 15, 22, 23, 25] do not adequately address the security concerns specific to Operators, leaving a significant gap in the ecosystem.

Thus, in this paper, we present the first in-depth research on the security vulnerabilities of Kubernetes Operators, focusing on the risks of cross-namespace reference vulnerability. The root cause of cross-namespace reference vulnerability lies in the mismatch between the declared scope of a resource and the effective scope of the Operator's logic. A resource may be declared as namespacescoped, allowing users with limited access to a single namespace to deploy it, while the Operator's logic may perform actions that affect other namespaces, breaking the intended isolation. We introduce two distinct tactics for exploiting Kubernetes Operators to elevate an attacker's privileges, both of which exploit the scope mismatch in Operator implementation and break the isolation between Kubernetes namespaces.

To aid in detecting these vulnerabilities, we designed and implemented detection tools that can identify scope mismatch in Operators, enabling users to assess and secure their systems against cross-namespace attacks. We conducted large-scale measurements of 2,268 Kubernetes Operators in the wild, revealing that over 14% of the Operators are potentially vulnerable to these attacks. We responsibly disclosed our findings to their developers, and, by the time of submission, 7 vulnerabilities had been confirmed and 6 CVEs were assigned or under assignment in response to our reports, affecting vendors including ****** and ******, highlighting the critical need for enhanced security practices in Kubernetes Operators.

All in all, our contributions can be summarized as follows:

- Attack Surface. We present the first systematic research on Kubernetes Operator security, specifically focusing on vulnerabilities that can be exploited in Operator implementations.
- Attack Tactics. We introduce the Cross-Namespace Reference Vulnerability, detailing two distinct tactics and their root cause, both of which can be leveraged to elevate an attacker's privileges.
- Automatic Detection. We design and implement tools for detecting vulnerabilities in Kubernetes Operators, enabling users to identify risks related to cross-namespace reference vulnerability.
- Real-World Measurement. We conduct large-scale measurements of Kubernetes Operators in the wild, demonstrating that over 14% of Operators are susceptible to these vulnerabilities.
- **Responsible Disclosure**. We responsibly disclosed our findings to the developers, and, by the time of submission, 7 vulnerabilities were confirmed and 6 CVEs were assigned or under assignment in response to our reports.
- Benefit Ecosystem. We open-source our tools to the community at https://anonymous.4open.science/r/Operator-Vuln-F05C, thereby fostering greater security awareness and improving the overall Kubernetes ecosystem.

2 Background

2.1 Kubernetes Namespace and RBAC

Kubernetes is a powerful container orchestration platform that automates the deployment, scaling, and management of containerized applications. It is designed to manage large-scale complex applications, where multiple teams or applications may share a single cluster. To help organize and isolate resources within the cluster, Kubernetes provides a mechanism called *Namespaces* [8]. A namespace is a logical partition or a virtual cluster within a physical cluster. Each namespace acts as a boundary, ensuring that resources in one namespace do not conflict with those in another.

Namespaces are particularly useful in multi-tenant environments, where different teams or applications share the same Kubernetes cluster [7]. By isolating resources in separate namespaces, Kubernetes prevents one team from accessing or interfering with another team's resources. This isolation is vital for security and resource management, ensuring that users and applications can only access the resources assigned to their namespace, preventing unauthorized access or potential conflicts between resources.

Kubernetes employs multiple security mechanisms to help ensure that the cluster remains secure and that resources are properly isolated. One of the most important mechanisms for securing access to resources within a namespace is RBAC (Role-Based Access Control) [29]. RBAC allows administrators to define roles with specific permissions and bind those roles to users or service accounts, ensuring that only authorized entities can perform certain actions. Cluster administrator can grant both namespace-specific permissions and cluster-level permissions. Specifically:

• *Role* and *RoleBinding*: Define and grant resource permissions within a specific namespace to a user, group, or service account.

• *ClusterRole* and *ClusterRoleBinding*: Define and grant resource permissions across all namespaces to a user, group, or service account.

2.2 Kubernetes Resource

At its core, Kubernetes organizes the cluster's state using resources, which are data objects encapsulating configuration and runtime information. Kubernetes manages many types of resources within a cluster, which are fundamental components that define the desired state of applications and services. Common built-in resources types include pods [27] and deployments [14]. A pod is the smallest deployable unit in Kubernetes and typically represents one or more containers that share the same network and storage resources. A deployment is a higher-level abstraction that manages the lifecycle of pods, specifying the desired number of pod replicas. In addition to built-in resources, Kubernetes allows users to define *Custom Resources* (CRs) [2], extending Kubernetes to manage domain-specific requirements beyond its default capabilities. Each type of Custom Resource is described by a Custom Resource Definition (CRD) [2], which specifies the resource's schema.

In Kubernetes, each type of resource, whether a built-in resource or a Custom Resource, is bound with an explicit scope, indicating its accessibility and impact within the cluster. Resources can be either *Namespace-scoped* or *Cluster-scoped*. In Kubernetes, the scope of built-in resources is embedded within the Kubernetes implementation, whereas the scope of Custom Resources is explicitly defined in their associated Custom Resource Definitions. Namespace-scoped resources must reside within a specific namespace, meaning they are logically isolated and can be accessed or manipulated by users with only Namespace-specific Roles. Conversely, Cluster-scoped resources exist at the cluster level and are not confined to any single namespace. These Cluster-scoped resources may affect or interact with all namespaces across the cluster. Due to their broad impact, accessing or manipulating cluster-scoped resources requires users to possess a cluster-wide ClusterRole, reflecting elevated privileges.

Importantly, resources themselves merely represent desired configurations or states. To realize these desired states, each type of resource is managed by an associated controller, a program responsible for monitoring resources and taking actions to align the actual state with the desired state described by resources. For example, the *deployment controller* monitors *deployment* resources and ensures that the desired number of pod replicas are running. If a pod fails or is deleted, the *deployment controller* automatically creates a new pod to meet the desired state. For built-in resources, Kubernetes provides native controllers. For Custom Resources, users should develop custom controllers.

2.3 Kubernetes Operator

A Kubernetes Operator is a method of automating and managing the lifecycle of complex applications on top of Kubernetes by extending the platform's native capabilities. Originally introduced by CoreOS (now part of Red Hat), it emerged from a recognition that while Kubernetes excels at automatically orchestrating workloads, many organizations need a more powerful automation pattern to handle full lifecycle management, such as database management, application upgrades, or failure recovery, that requires specific operational

```
1 apiVersion: example.com/v1
2 kind: DatabaseInstance
3 metadata:
4 name: my-database
5 spec:
6 replicas: 3
7 storageSize: "10Gi"
```

Figure 1: Custom Resource Example

knowledge. Operator is thus introduced to extend Kubernetes by embedding human operational expertise into software, enabling automated management of complex, stateful applications.

An Operator consists of one or more Custom Resource Definitions (CRDs) and their corresponding Custom Resource Controllers. CRD defines the schema of a custom resource type that will be processed by the Operator. Controllers work with CRDs by continually monitoring the custom resources and taking actions to fulfill the operational tasks requested by users.

To use an Operator, users manipulate custom resources that represent the operational task along with the related parameters they want to conduct. The Operator controller reads these custom resources, takes actions listed in the custom resource, and ensures that the operational task behaves as expected. Considering an Operator for database management tasks, users may create a custom resource listed in Figure 1, including arguments like the number of database replicas and storage settings. The Operator controller then reads the custom resource, automatically provisions, scales, and maintains the database according to these specifications.

Since Operators typically manage multiple kinds of resources across namespaces, they often run with elevated RBAC privileges, allowing them to create, modify, and delete resources on behalf of users. This makes them powerful but also introduces security risks. If an Operator does not adopt proper security measures, attackers may exploit the vulnerabilities of the Operator to gain unauthorized access or manipulate resources beyond their intended scope.

3 Threat Model

Our threat model aligns with real-world Kubernetes deployments where multiple tenants, teams, or applications share the same cluster while being isolated within their respective namespaces [7]. The adversary aims to break Kubernetes namespace isolation and achieve cross-namespace privilege escalation by exploiting security weaknesses in Operator implementations. Their objectives are performing operations in unauthorized namespaces (i.e., namespaces that they have no *Roles*) and thus escalating privileges.

We assume the Kubernetes cluster deploys vulnerable Operators, and the adversary has legitimate access to a Kubernetes cluster but can only access their authorized namespaces. Thus, they can not access or manipulate cluster-scoped resources and can only interact with Operators by manipulating namespace-scoped resources in their authorized namespace. They seek to leverage vulnerable Kubernetes Operators to execute unauthorized operations in other namespaces. The adversary may be:

- A malicious tenant in a multi-tenant cluster who is only authorized to access their assigned namespace.
- A compromised application running in a namespace with namespace-level permissions mounted.

It is notable that our threat model is significantly different from previous works [31, 47]. Specifically, existing works assume that the adversaries have direct control over the vulnerable application containers, which is a strong assumption in the real-world. In contrast, within our threat model, an adversary does not have access to Kubernetes work nodes or direct control of Operator containers. They cannot directly access containers of Operators since these Operators may be deployed in adversary-unauthorized namespaces. In extreme cases, Operators can even be deployed outside the Kubernetes cluster [3]. So the threat model of previous works [31, 47] is relatively infeasible, but our threat model is more feasible and aligned with real-world scenarios.

4 Cross-Namespace Attacks

4.1 Attack Overview

In Kubernetes clusters, namespaces act as virtual boundaries, restricting user access and isolating resources. Kubernetes Operators manage applications and resources and perform essential operational tasks. While these Operators simplify application management, their inherent privileges and operational flexibility create potential security vulnerabilities that can be exploited for crossnamespace reference attacks.

The high-level attack flow is as follows: an attacker, who has legitimate but restricted access to one namespace, manipulates a maliciously crafted namespace-scoped resource instance within their authorized namespace. The Operator, continuously watching for namespace-scoped resource events, detects this malicious resource instance and processes it with privileged operations that impact namespaces beyond the attacker's authorized scope, effectively breaking the intended namespace isolation enforced by Kubernetes.

Root Cause. The core enabling cross-namespace reference attacks stems from a mismatch between the declared scope of a resource and the actual scope of its process logic. Specifically, the vulnerability arises when the scope of a resource is defined as *Namespaced*, indicating that each instance should strictly reside within its assigned namespace. Thus an adversary only with *Role* in a single namespace may manipulate such a resource in their namespace. However, despite this namespace-scoped definition, the Operator may actually perform operations across namespaces, inadvertently allowing manipulation of resources in namespaces beyond the intended scope. As a result, an adversary without *Role* in other namespaces may invoke the Operator to escalate their permissions and access unauthorized namespaces.

Cross-Namespace Features. There are two primary scenarios that enable cross-namespace reference actions. First, when processing namespace-scoped resources in one namespace, an Operator may access or manipulate other namespace-scoped resources in a different namespace (§4.2). Second, when processing namespace-scoped resources, an Operator might access or manipulate cluster-scoped resources, leading to impacts on the whole cluster across all namespaces (§4.3). Both scenarios allow adversaries to trick the Operator into performing unintended, privileged operations beyond the adversary's RBAC scope.

4.2 Insecure Namespace-Scoped Resource Reference

Insecure Namespace-Scoped Resource Reference vulnerability arises when an Operator processing namespace-scoped resources, the fields of which are then used by the Operator to reference resources in other namespaces. This vulnerability fundamentally undermines Kubernetes namespace isolation by enabling attackers to indirectly access resources from namespaces they are otherwise restricted from accessing.

Attack Flow. As illustrated in Figure 2, consider two namespaces: an attacker namespace and a victim namespace containing sensitive resources. The Roles and RoleBindings claim that the attacker can only access resources in their namespace and cannot access those in the victim's namespace.

To bypass the restriction of RBAC and access resources in unauthorized namespaces, the attacker first crafts and deploys a malicious resource instance within their namespace. This resource includes fields leveraged by the Operator to reference resources located in the victim namespace. From the perspective of Kubernetes, the deployment of the malicious resource should be allowed because it only knows that the attacker has created a resource under their authorized namespace, but does not know if the resource leads to privilege escalation.

The Operator then processes the newly created malicious resource. The Operator extracts the fields in the malicious resource, operates the victim resource located in the victim namespace, and inadvertently leaks or tampers with sensitive information. Thus, the attacker effectively escalates their privileges, bypassing Kubernetes' namespace isolation, gaining unauthorized access to resources that should have remained secure.

Example. A common real-world scenario occurs when an Operator manages applications consuming credentials (e.g., API Secret Key) stored in Kubernetes Secrets. As per Kubernetes official security practice [4], Secrets should only be referenced strictly within the same namespace to maintain proper isolation.

However, the vulnerable Operator implements cross-namespace references by setting up a *secretRef.namespace* field in its custom resource definition. Given this insecure implementation, an attacker restricted to a namespace could craft the malicious custom resource as illustrated in the upper YAML file of Figure 3. He deploys a resource with *metadata.namespace* setting to *attacker*, which means the resource is deployed in the *attacker* namespace. This deployment is allowed since the RBAC authorized the attacker to work in his own namespace. In the specification of the resource, the attacker defines the value of *secretRef* at Lines 8-11, referencing a Secret named *sensitive-secret* in his unauthorized namespace *victim*.

The Operator notices the malicious resource deployed by the attacker, reads the *secretRef* field at Line 3 of the Reconcile function illustrated in Figure 3. The name and namespace of the referenced victim Secret are then loaded into the *namespacedName* object, which is used to query and retrieve the specified Secret into the *secret* object at Line 13. The remaining parts of the Operator will consume the content of the Secret to perform further operations.







Figure 3: Insecure Namespace-Scoped Resource Reference Sample

Impact. Insecure Namespace-Scoped Resource Reference vulnerabilities fundamentally enable attackers to escalate privileges by allowing them to reference and manipulate resources in namespaces beyond their legitimate access. Further impact of this vulnerability heavily depends on how the Operator processes and utilizes the referenced resources, as well as the nature of the referenced resources themselves. For instance, if the referenced resource is a Kubernetes Secret containing sensitive credentials like API Tokens, an attacker may obtain unauthorized access to applications, databases, or cloud infrastructure. If the Operator not only reads but also modifies referenced resources, attackers might disrupt service availability, modify application configurations, or inject malicious workloads. Thus, the severity and scope of the impact are highly context-dependent, ranging from sensitive information leakage to complete cluster compromise, based on the type and usage of the improperly referenced resource.

4.3 Insecure Cluster-Scoped Resource Reference

Insecure Cluster-Scoped Resource Reference occurs when a Kubernetes Operator processes a namespace-scoped resource and interacts with cluster-scoped resources. Unlike namespace-scoped resources that remain isolated within specific namespaces, clusterscoped resources affect the entire Kubernetes cluster. If an Operator allows users to influence these cluster-scoped resources through namespace-scoped resources, it creates a pathway for attackers to escalate privileges and potentially compromise the entire cluster. **Attack Flow**. As illustrated in Figure 2, consider a namespace controlled by an attacker named *attacker*, and all the other victim namespaces. The Roles and RoleBindings in the cluster define that the attacker can only access resources in their namespace and cannot access any victim's namespace.

The basic attack workflow for this vulnerability starts with an attacker creating a malicious resource in their authorized namespace, whose fields are leveraged by the Operator to reference a clusterscoped resource. The Operator, running with elevated cluster-level privileges, processes this malicious input and subsequently performs operations on the referenced cluster-scoped resource. As cluster-scoped resources inherently affect the entire Kubernetes environment, these unauthorized accesses and manipulations enable attackers to escalate privileges beyond their initial namespace boundaries and gain control or influence over all the other namespaces.

Example. Operators often interact with cluster-scoped resources,



Figure 4: Insecure Cluster-Scoped Resource Reference Sample

ClusterRole or ClusterRoleBinding, because some applications require elevated or cluster-wide permissions to operate correctly. An insecure implementation occurs when an Operator accepts namespace-scoped resources and assigns a ClusterRole and ClusterRoleBinding to the requesting namespace. An attacker restricted in a namespace could thus craft the malicious resource illustrated in the YAML file of Figure 4. He deploys a resource with *metadata.namespace* setting to *attacker*, which means the resource is deployed in the *attacker* namespace.

The Operator monitors *App* custom resources. It finds the malicious resource deployed by the attacker, and creates Cluster-RoleBinding towards a ServiceAccount in the attacker's namespace. Thus, the attacker can impersonate the ServiceAccount in his authorized namespace to escalate his privilege, gaining cluster-level permissions.

Impact. Insecure Cluster-Scoped Resource References allow attackers to escalate privileges and affect resources across all namespaces in a cluster. The specific severity and effect of this vulnerability depend on which cluster-scoped resources the Operator interacts with. For instance, if an Operator insecurely assigns a ClusterRole or ClusterRoleBinding as dictated by namespace-scoped resources, an attacker can gain cluster-level permissions. The detail permissions assigned depend on the implementation of Operators.

5 Cross-Namespace In The Wild

To assess the prevalence of the vulnerabilities described in Section 4, we conducted a large-scale measurement of real-world Kubernetes Operators and disclosed our findings to affected vendors.

Table 1: Common Operator-Related Libraries

Library	Description
k8s.io/api [19]	K8s Built-In Resource Specifications
k8s.io/apimachinery [20]	K8s Metadata Specifications
client-go [21]	K8s Official Client
client-gen [16]	K8s Official Client Generator
controller-runtime [17]	Controller Client
Kubebuilder [18]	Operator Framework
Operator SDK [26]	Operator Framework

5.1 Measurement Methodology

5.1.1 Overview. To understand how widespread the vulnerabilities are in real-world Kubernetes Operators, we perform a systematic measurement illustrated in Figure 5, which consisting of the following steps:

- Operator Collection: A large set of publicly available Kubernetes Operator repositories is collected from GitHub.
- (2) Resource Type Identification: Resource types (either Kubernetes built-in resources or custom resources) used by each Operator are extracted, and their declared scopes (either namespacescoped or cluster-scoped) are identified based on the code.
- (3) Vulnerability Detection: The analysis identifies whether Operators process namespace-scoped resources but conduct insecure cross-namespace reference behavior, as depicted in Section 4.2 and Section 4.3.
- (4) Summary: Identified vulnerabilities are further aggregated based on the types of referenced resources and operation verbs to evaluate the impacts in the real world.

Since the two dominant Kubernetes Operator frameworks with the highest GitHub Stars, Kubebuilder [18] and Operator SDK [26], are written in Golang, the collection specifically targets Operators implemented in Golang. We adopted CodeQL [12] v2.17.4 to analyze Operators. The entire CodeQL query suite uses around 1,500 lines of QL rules.

To enhance the measurement process, 7 commonly used libraries listed in Table 1 were modeled to accurately resolve and track Kubernetes interactions within collected Operator implementations. They contain specifications of native Kubernetes resources, namespacerelated data structures, and functions for Operators to manipulate resource. The detail is elaborated later.

5.1.2 Operator Collection. The dataset of Kubernetes Operators analyzed was collected by crawling GitHub repositories. To achieve this, GitHub Search API [1] was utilized with the query string *"Kubernetes Operator language:go"*. The collection process strictly adhered to GitHub's API rate limits and usage guidelines to responsibly retrieve relevant Operator repositories.

After collecting Operators from GitHub, we set up CodeQL databases for each Operator. Operators that cannot be compiled to generate the CodeQL database due to errors, like syntax and dependency errors, are eliminated, and the final set contains 2,268 Operators.



Figure 5: Measurement Workflow

5.1.3 *Resource Type Identification.* The first critical step in detecting vulnerabilities is Resource Type Identification, as the attack requires the attacker to initiate operations using a namespace-scoped resource they are authorized to create in their own namespace. The analysis separately handles Kubernetes Built-in Resources and Operator-defined Custom Resources.

Custom Resource Identification. For Custom Resources defined by the Operators, their data structures can be explicitly extracted from the source code. In Kubernetes, each resource structure must contain a field of type TypeMeta (defined by the *Apimachinery* library [20]), which acts as the unique identifier of a resource type. Thus the analyzer extracts all struct types in Operators and filter those with TypeMeta fields. This outputs all custom resource types in Operators.

To further identify the scope of each resource type (namespace or cluster), common Operator frameworks like Kubebuilder [18] and Operator SDK [26], as well as Kubernetes' official client code generator [16], require developers to explicitly decorate clusterscoped resource structs using special marker annotations "+genclient:nonNamespaced" or "+kubebuilder:resource:scope:Cluster". By detecting these markers in the Custom Resource struct definitions, the analyzer reliably identifies Custom Resource types in Operators as well as their scopes.

Kubernetes Built-in Resources. Unlike Custom Resources, the built-in Kubernetes resource specifications are imported from the external *k8s.io/api* [19] library to Operators, thus their source code and scope markers are not directly accessible for CodeQL. Therefore, the analyzer adopts an alternative method. Specifically, Operators would ultimately depend on the *client-go* library [21]. Each type of built-in Kubernetes resource is uniquely associated with a typed client provided by the *client-go* library [21]. Each typed client is constructed by methods in its corresponding *Getter* interfaces under the *k8s.io/client-go/kubernetes/typed* package. For example, considering the built-in resource type *Pod*, there is a uniquely associated Pod client. The Pod client is constructed by the only method in the *PodGetter* interface. By extracting the return types of methods in all *Getter* interfaces, the analyzer identifies all built-in types and their clients.

Table 2: Resource Namespace Setters

imachinery
imachinery
)

Function	Library
ApplyConfiguration.WithNamespace()	client-go
*.SetNamespace()	k8s.io/apimachinery
Constructor of Typed Client	client-go
Constructor of Typed Client	client-gen

To determine the scope of built-in resources, the analysis leverages the only method in the *Getter* interface of each typed client. Specifically, namespace-scoped resource clients in client-go require a *namespace* parameter in their constructor to specify the target namespace. In contrast, constructors for cluster-scoped resource clients do not require such a namespace argument. By counting and verifying constructor parameters, the analysis distinguishes namespace-scoped from cluster-scoped built-in resources.

5.1.4 Vulnerability Detection. This step determines whether an attacker-controlled input can influence sensitive operations that cross namespace boundaries or impact the whole cluster. To achieve this, the analysis uses interprocedural taint tracking, tracing the propagation of data originating from the namespace-scoped resource objects to insecure reference sites in the controller logic.

Insecure Namespace-Scoped Resource Reference. The goal of this detection is to determine whether attacker-controlled values can be used to specify the namespace of another resource by the Operator. This is essential because if the attacker can influence which namespace a referenced resource belongs to, they can trick the Operator into accessing or modifying resources beyond their authorized scope.

Thus, the analysis tracks data flow from namespace-scoped resource objects to namespace setters (listed in Table 2) that are

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leveraged to specify the namespace of a resource. We identify 3 struct fields that can store namespace values in 2 libraries. We identify 4 types of functions in 3 libraries that can be used to set the namespace field of a resource object or set up a typed client towards a specific namespace.

It is worth noting that the 3 fields (listed in Table 2) of namespacescoped resource objects are excluded from the taint source, as these fields denote the namespace where this resource is deployed. Since the attackers are only authorized to access their namespace, the namespace fields of attacker-controlled resources are always the attacker-authorized namespace. If these fields sink in the referenced resources' namespace fields, it means the referenced resources are also in the attacker-authorized namespace. Thus, no cross-namespace operation is conducted.

Taking the above key points into consideration, if the tainted data flows into any of these namespace setters, the Operator is flagged as potentially vulnerable to insecure namespace-scoped resource references.

Insecure Cluster-Scoped Resource Reference. This analysis aims to detect whether attacker-controlled input can influence cluster-scoped resource. Since these cluster-scoped resources affect the entire Kubernetes cluster, any modification to them based on namespace-scoped input represents a significant privilege escalation risk. Thus, the analysis tracks data flow from the identified namespace-scoped resource objects into any cluster-scoped resource objects. If tainted input is used to construct such clusterscoped resource objects, the Operator is flagged as vulnerable to insecure cluster-scoped resource references.

5.1.5 Summary. To understand what an adversary can do to which kind of resource, the measurement further identifies insecure referenced resource types and operations towards these resources.

Affected Resource Type Identification. This step discovers which resource can be referenced by an adversary. This identification is trivial for insecure cluster-scoped resource references, as their sink site in the vulnerability detection phase is set to cluster-scoped resource objects. Thus, the affected cluster-scoped resource types can be directly extracted from sink objects.

For insecure namespace-scoped resource references, the affected resource type identification depends on the type of sink site in the previous step. If the previous data flow sinks at the three fields, *WithNamespace()*, or *SetNamespace()* methods, then the analyzer further tracks interprocedural data flow from the previous sinks to any namespace-scoped resource objects to identify affected resource objects and types. If the previous data flow sinks at the constructor of a typed client, then the resource type is the one associated with that typed client.

Verb Identification. To understand what an adversary can do to the insecurely referenced resources, the analyzer identifies the Kubernetes API Verbs (e.g., Get, Create, Update, Delete, etc.) related to insecurely referenced resources. If an insecurely referenced resource is found to be related to a Verb, like Create, then the adversary can exploit the vulnerable Operator to create the insecurely referenced resource in the Kubernetes cluster, which they should not.

Verb identification is achieved by identifying client method invocations that accept insecure references. For *controller-runtime*



Figure 6: Percentage of Affected Operators

library, it processes all resource types by a unified typeless client in the *sigs.k8s.io/controller-runtime/pkg/client* package. For *client-go* and *client-gen* libraries, they process each type of resource with a specific typed client. Each Kubernetes API Verb corresponds to the client method with the same name. The analyzer thus performs interprocedural taint tracking from the reference site to these client methods to identify the related verbs.

5.2 Measurement Result

We conducted measurements on 2,268 Operators crawled from GitHub to assess the real-world impacts of insecure cross-namespace references and answer the following research questions:

- **RQ1**: How many operators are potentially vulnerable to insecure cross-namespace reference?
- **RQ2:** What resources can be cross-namespace referenced by attackers?
- **RQ3**: What can an attacker do towards cross-namespace referenced resources?
- **RQ4**: How can insecure cross-namespace references impact the real world?

5.2.1 RQ1: How Many Operators Are Potentially Vulnerable To Cross-Namespace Reference? To assess the prevalence of insecure cross-namespace reference vulnerabilities, we analyzed a dataset of 2,268 real-world Kubernetes Operators collected from GitHub. Each Operator was examined to determine whether attacker-controlled namespace-scoped resources can influence operations across namespace boundaries. The results are summarized as follows:

- 143 Operators (6.3%) only include insecure namespace-scoped resources references that can specify or influence operations on other namespaces.
- 122 Operators (5.4%) only contain insecure cluster-scoped resource references, where attacker-controlled namespace-scoped resources can affect cluster-scoped resources.
- 52 Operators (2.3%) allow both types of references, posing risks of privilege escalation at both the namespace and cluster level.

These findings show that a non-negligible portion (over 14%) includes logic that may lead to privilege escalation, highlighting a widespread but largely overlooked security concern in the Kubernetes ecosystem.

Table 3: Major Insecurely Referenced Resource Type

Scope	Resource Type	Ref By #Op.
	Secret	102
Namespace	ConfigMap	29
	Deployment	29
	Service	22
	StatefulSet	12
Cluster	Namespace	62
	ClusterRoleBinding	40
	ClusterRole	26
	Node	25
	PersistentVolume	15



Figure 7: Reference of Built-In and Custom Resources

5.2.2 RQ2: What Resources Can Be Cross-Namespace Referenced By Attackers? To understand the attack surface exposed by insecure cross-namespace references, we investigate the types of resources that Operators allow attackers to reference across namespace boundaries. For each resource type, we count the number of Operators that insecurely reference it and analyze which types are most frequently involved in such behavior.

Among namespace-scoped resources, the most commonly insecurely referenced types (listed in Table 3) are Secret (referenced by 102 Operators), ConfigMap (29 Operators), and Deployment (29 Operators). In Kubernetes, Secrets store highly sensitive data such as API keys, credentials, and TLS certificates. ConfigMaps often contain important application configurations that control applications behavior, like API endpoints and performance arguments. Deployments define and manage the application workloads by controlling replica sets and pods.

For cluster-scoped resources, the most common insecurely referenced types are Namespace (62 Operators), ClusterRoleBinding (40 Operators), and ClusterRole (26 Operators). In Kubernetes, Namespaces are resources that define the namespace in a Kubernetes cluster. ClusterRoles and ClusterRoleBindings define and grant cluster-level permissions that apply in the whole cluster.



Figure 8: Verbs Used By # Operators Towards Insecurely Referenced Resources

We also distinguish between insecure references to built-in Kubernetes resources and custom resources. To this end, we aggregated the type-#Operator result above based on built-in resource type or custom resource type. For insecure namespace-scoped references, 279 cases involved built-in resources and 182 involved custom resources. For insecure cluster-scoped references, 211 targeted built-in resources and 87 involved custom resources. These results indicate that insecure references can affect both built-in resources and custom resources. And the insecure references are more commonly associated with Kubernetes built-in resources.

5.2.3 RQ3: What Can Attacker Do Towards Cross-Namespace Referenced Resources? To understand the potential impact of insecure cross-namespace references, we analyze the operations (Kubernetes API Verbs) that Operators perform on the referenced resources. For each identified insecurely referenced resource, we extract its related verbs. We then count how many Operators apply each verb to each insecurely referenced resource type. The result is illustrated in Figure 8.

For insecurely referenced namespace-scoped resources, the top three most common verbs are *Get* (used by 188 Operators), *Create* (74 Operators), and *Update* (61 Operators), with *Get* being the most prevalent. In Kubernetes, *Get* retrieves the current state of a resource, *Create* instantiates a new resource, and *Update* modifies an existing resource. The predominance of the *Get* operation indicates that a large number of vulnerable Operators retrieve data from resources in other namespaces based on attacker-controlled inputs, exposing unauthorized data to attackers.

For insecurely referenced cluster-scoped resources, the top three verbs are *Get* (used by 141 Operators), *Create* (88 Operators), and *Update* (57 Operators), with *Get* accounting for the largest proportion. This suggests that in many cases, Operators may use attacker-influenced data to get cluster-wide resources, which may expose sensitive cluster-level information to attackers.

To further understand the practical implications, we investigate the verb-resource pairs (i.e., combinations of verbs and insecurely referenced resource types) to determine which verbs Operators



Figure 9: Verbs of Major Resources

Table 4: Major Insecurely Used Verb-Resource Pairs

Scope	Verb - Ref.Resource Type	Used By #Op.
	Get - Secret	97
Namespace	Get - ConfigMap	25
	Get - Deployment	25
	Create - Secret	21
	Update - Secret	19
	Get - Namespace	51
Cluster	Create - ClusterRoleBinding	33
	Create - Namespace	30
	Create - ClusterRole	23
	Get - Node	20

typically perform on specific insecurely referenced resource types. The result is illustrated in Table 4 and Figure 9.

For insecurely referenced namespace-scoped resource types, the most prevalent pairs are *Get-Secret* (used by 97 Operators), *Get-ConfigMap* (25 Operators), and *Get-Deployment* (25 Operators). These indicate that a substantial number of Operators can be exploited to read data from Secrets, configuration files, or application deployments in attackers' unauthorized namespaces, causing information exposure.

For insecurely referenced cluster-scoped resource types, the most prevalent pairs are *Get-Namespace* (used by 51 Operators), *Create-ClusterRoleBinding* (33 Operators), and *Create-Namespace* (30 Operators). These patterns suggest that Operators may be exploited to reveal other namespaces in the cluster, assign cluster-wide permissions, or provision new namespaces, leading to privilege elevation.

Together, these findings highlight that insecure cross-namespace references are not only present but often tied to high-impact operations on sensitive or privileged Kubernetes resources.

5.3 RQ4: Case Study

We responsibly disclosed vulnerabilities to affected vendors. The case study is hidden due to embargoes.

6 Mitigation

During our inspection of vulnerable Operators, we realized that Operators aim to simplify user operations as much as possible, thus may embed cross-namespace reference functionality to spare users the repetitive, manual task of duplicating resources like Secrets across namespaces—a practice necessitated by Kubernetes' namespace isolation. However, this convenience can inadvertently introduce vulnerabilities if not properly implemented, as attackers may exploit such "helpful" behavior to perform unauthorized crossnamespace actions and privilege escalations. Thus, we suggest the following mitigations to eliminate the insecure cross-namespace reference vulnerability.

Scope Alignment. Developers should ensure that the declared scope of resources accurately reflects the scope of their operational effect. If a resource is defined as namespace-scoped but its process logic performs actions across multiple namespaces at the cluster level, it creates a dangerous mismatch between the resource's access control boundary and its actual impact. In such cases, the resource should be explicitly declared as cluster-scoped, ensuring that only privileged users can create or manipulate it.

Avoid Uncessary Cross-Namespace References. Operator developers should avoid supporting unnecessary cross-namespace references in Custom Resource specifications. Whenever possible, references to other resources, such as Secret and ConfigMap, should be limited to the same namespace as the Custom Resource itself. If cross-namespace references are truly required, it is suggested to receive such requests from cluster-scoped resources, ensuring users have enough permissions and no privilege escalation occurs. Minimize User Permissions. While an Operator may legitimately require elevated permissions, such as reading Secrets across namespaces, to fulfill its responsibilities, these privileges often cannot be further minimized without breaking functionality. However, permission minimization can still be enforced at the user side. In multi-tenant environments, cluster administrators should minimize user permissions to prevent low-privileged users from exploiting Operators. Role-based access control (RBAC) should be configured so that only trusted users or service accounts can interact with sensitive resources. By carefully controlling who can invoke the Operator, administrators can prevent tenants from abusing it to perform unauthorized cross-namespace or cluster-level operations. Future Work: Finer Access Control. A fundamental limitation in the current Kubernetes architecture is that Operators typically lack visibility into who initiated a resource request. As future work, we aim to design and implement a mechanism for Operators to authenticate and verify the identity of the request user associated with a resource event. This capability would allow Operators to enforce that privileged operations are only performed on behalf of users with appropriate permissions, strengthening the security of Kubernetes Operators in multi-tenant environments.

7 Related Work

Kubernetes Operators and Controllers. Existing research on Kubernetes operators and controllers focuses on functional bugs instead of security vulnerabilities. Gu et al. [30] proposes an automatic end-to-end testing technique for validating the operational correctness of Kubernetes Operators. Acto continuously generates desired state declarations and verifies whether the Operator correctly reconciles the system to those states. Sun et al. [41] presents an automatic reliability testing framework for cluster-management controllers. By injecting faults, Sieve uncovers deep semantic bugs by observing how controllers behave under fault conditions they are expected to tolerate. Sun et al. [42] presents the formal verification framework for Kubernetes controllers via TLA-style temporal reasoning, validating whether controllers eventually bring the cluster to the desired state and maintain it. Liu et al. [34] verifies Kubernetes controllers and their configurations by modeling controller behaviors and checking for violations of user-defined intent properties using model checking. It detects issues like imbalance and lifecycle bugs, focusing on functional correctness. Xu et al. [46] systematically summarizes historical functional bugs of Operator.

To the best of our knowledge, our work is the first comprehensive study on Kubernetes Operator security.

Kubernetes Security. In terms of attack and exploitation techniques, MITRE [24] and Microsoft [28] summarize tactics to compromise containers and container orchestration systems like Kubernetes. Pecka et al. [35] investigates privilege escalation scenarios for DevOps pipelines on Kubernetes. He et al. [32] presents crosscontainer attacks on Kubernetes with eBPF. Spahn et al. [40] sets up honeypots on Kubernetes and analyzes the attacks towards containers and container orchestration systems. Shringarputale et al. [39] presents a co-residency attack towards container orchestration systems. Zeng et al. [48] comprehensively analyzes 30 vulnerabilities in Kubernetes stacks. However, these attacks have not included the security issues brought about by Kubernetes operators.

Kubernetes offers extensive configuration options for managing applications, including access controls and specifying security contexts. Any misconfigurations can lead to severe security vulnerabilities. Thus, another theme of Kubernetes security research is eliminating misconfiguration. Islam Shamim et al. [33] systematically identifies best practices to secure Kubernetes clusters. Shamim et al. [38] conducts an empirical study and reveals the disconnection between Kubernetes configuration recommendations and real-world practices. Rahman et al. [36] designs static analysis tools and conducts a large-scale empirical study on Kubernetes manifests, revealing the landscape of misconfiguration. Ul Haque et al. [44] leverages knowledge graphs to detect and mitigate Kubernetes misconfiguration. Shamim [37] explores the risk of misconfiguration when violating Kubernetes security best practices. Recent work Yang et al. [47] identifies the security risk of excessive Kubernetes RBAC permissions, which may lead to whole cluster takeover. Gu et al. [31] follows up the research and designs systems to automatically minimize RBAC permissions. The industry also presents numerous tools for Kubernetes security, including Trivy [11], Kubescape [22], KubeSec [13], KubeArmor [15], Open Policy Agent [25], and Kyverno [23], providing functions like misconfiguration detection and runtime policy enforcement.

While the existing works try to address misconfiguration and thus achieve the Principle of Least Privilege (PoLP) for applications, the vulnerability we present is not simply misconfigurations or violations of PoLP. They arise from inherent flaws in how Operators process user-controlled resources. These vulnerabilities exist even when the permissions of Operators are minimal in the current Kubernetes architecture, highlighting a deeper design-level security gap in the Operator model itself.

8 Conclusion

In this paper, we presented the first research on the security issues of Kubernetes Operators. We introduced Cross-Namespace Reference Vulnerability with two strategies, demonstrating how an attacker can bypass namespace isolation. We designed and implemented a static analysis suite to detect such vulnerabilities. Large-scale measurements illustrated that over 14% of Operators in the wild are potentially vulnerable. Our findings have been reported to the relevant developers, resulting in 7 confirmations and 6 CVEs by the time of submission, highlighting the critical need for enhanced security practices in Kubernetes Operators. We proposed possible mitigation solutions and open-sourced the static analysis suite to benefit the ecosystem.

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